SIMULATION OF EMITTANCE GROWTH USING THE UAL STRING SPACE CHARGE MODEL

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Abstract

Evolution of short intense electron bunches passing through bunch-compressing beamlines is simulated using the UAL (Unified Accelerator Libraries) string space charge formulation.[1] Excellent agreement is obtained with results obtained experimentally at CTF-II, the CERN ``Compact Linear Collider" test facility[2]. The 40 MeV energy of these data is low enough for Coulomb and Biot-Savart forces to be important and high enough for coherent synchrotron radiation and centrifugal space charge forces to be important. UAL results are also compared with CSRtrack [3] results for emittance growth in a 50 MeV "standard" chicane. Vertical space charge forces are found to be important in this (low energy) case.

CALCULATIONAL MODEL

Particles are treated as strings as regards their fields but as points as regards their dynamics. Bunch evolution is treated as standard tracking but with intrabeam scattering. The force on particle A due to the (properly-retarded) field of the string associated with particle B is expressed in terms of (closed-form) elliptic integral functions. In the (rare) case when the bunch straddles a magnet edge all particles are assumed to be on the same side of the edge as A. All results have become essentially independent of the number N of macroparticles for N>400, but N-values as great as 3200 have been used in some cases. Summed over all B, for every particle A there are N impulses, making N-squared calculations per evolution step. Even so, all calculations have been done on a laptop.

CSR (coherent synchrotron radiation) results from self-work of the bunch acting on itself---validity of Newton's third law requires the inclusion of field momentum. All static (electric and magnetic) forces plus all coherent longitudinal (CSR) and transverse CSCF (centrifugal space charge force), as well as radiative effects, are included. Since there is no need for "regularization" to suppress singularity, bends and drifts are treated homogeneously. Extreme relativistic approximations (such as neglect of vertical forces) are avoided.

SIMULATION OF CTF-II MEASUREMENTS

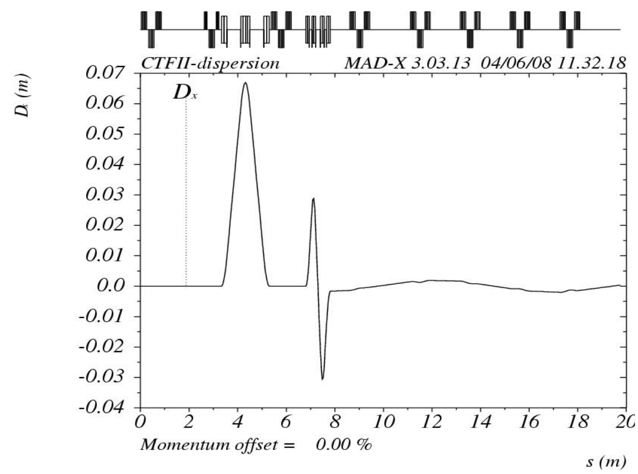

Figure 1: Beamline dispersion, showing "compressor" chicane (C shape) and "shielded" chicane (S shape).

Emittance growth in a bunch compressor has been studied experimentally[2] at the CTF-II (CERN Compact Test Facility), shown in Fig. 1, using electrons of energy 40 MeV. No shielding of CSR by vacuum chamber walls was detected, and the present simulation assumes this to be true. Input and output momentum spectra are shown in Fig. 2. Substantial momentum spreading is visible.

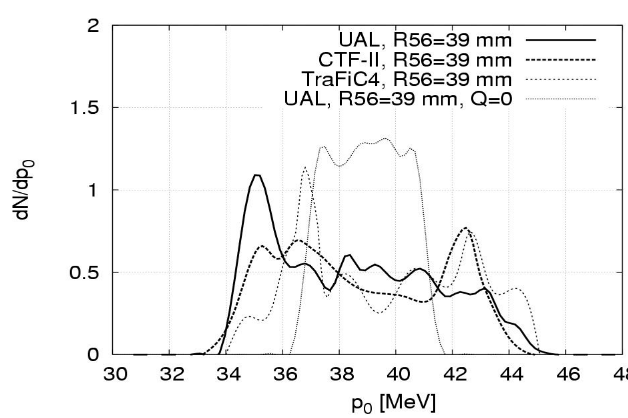

Figure 2: Bunch momentum spread at beamline output with no space charge (narrow square pulse) and with Q=10nC, as measured (label CTF-II) and as simulated by UAL and by (an early version of) TraFiC4.

Dependence of CSR energy loss on bunch length and on R56 value at S-chicane location, was measured for Q=15nC. See Fig. 3. The present simulation, having no empirically adjustable parameters, agrees well within error bars with the measurements. This confirms theoretical expectations concerning CSR.

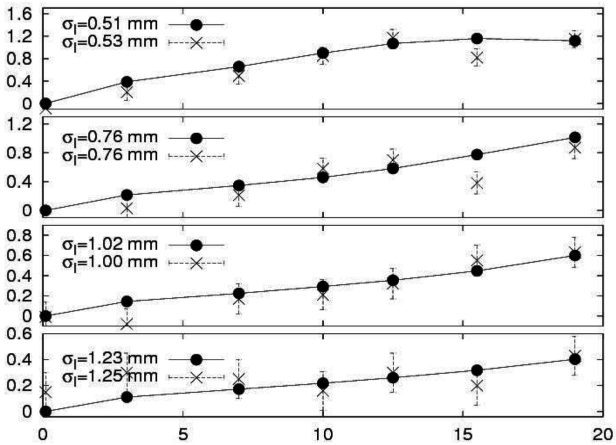

Figure 3: Energy loss in MeV as function of S-chicane R56 value in mm, for the four values of r.m.s. bunch length (adjusted using the C-chicane) labeling the figures. The measured values have error bars.

An unexpected (at the time) result reported was a quite strong increase in horizontal emittance for small beta function values at the C-chicane location (with S-chicane turned off). The data and simulation is shown in Figure 4. The present simulation agrees at least semi-quantitatively with the measurements.

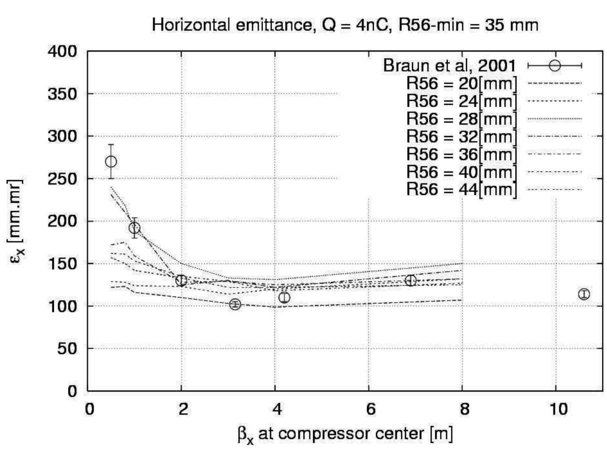

Figure 4: Dependence of output horizontal emittance on horizontal beta function at the C-compressor.

UAL CSRTRACK COMPARISON

To enable controlled comparison of UAL with the CSR-aware code CSRtrack[3], the 50 MeV benchmark chicane shown in Fig. 5 was designed. Parameters are given in Table 1. All distributions are Gaussian.

Table 1: Chicane and Beam Parameters

Chicane Parameters	Symbol	Value, Unit
Dipole length	L_B	0.50 m
Drift length	L_D	5.00 m
Drift length	L_i	1.00 m
Total chicane length	L_{tot}	13.00 m
Nominal bending angle	α_0	2.77 deg
Nominal momentum compaction	R_{56}	-25.00 mm

Electron Beam Parameters	Symbol	Value, Unit
Electron energy	E_0	50 MeV
Bunch charge	Q_0	1.0 nC
Initial rms bunch length	$\sigma_{s,i}$	200 μm
Initial peak current	$I_{p,i}$	600 A
Initial uncorrelated rms energy spread	$\sigma_{E,rms}/E_0$	0.01 %
Initial energy-position correlation	$1/E_0\, dE/ds$	-20.1 m^{-1}
Initial normalized emittance	$\epsilon_{n,x}$	1.0 mm mrad
	$\epsilon_{n,y}$	1.0 mm mrad
Twiss functions at chicane entrance	$\beta_{x,i}$, $\alpha_{x,i}$	80.41 m, 6.254
	$\beta_{y,i}$, $\alpha_{y,i}$	22.80 m, 3.110

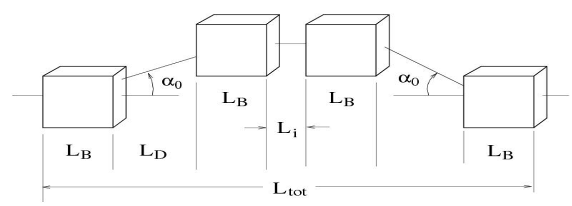

Figure 5: Chicane sketch.

Due to the low energy but high bunch intensity this benchmark case is deliberately made extreme regarding CSR emission and emittance blow-up.

To emulate CSRtrack (which neglects vertical intrabunch forces) the UAL simulation was run with all vertical intrabunch forces suppressed. This simplification is justified at high electrons energies since then the electromagnetic fields are confined to a narrow cone, i.e. vertical and also horizontal field components are small. But it should breakdown at low energies. Table 2 shows excellent agreement of simplified UAL and CSRtrack simulations for the benchmark case; the output vertical emittances 74.1 and 72.6 mm.mrad, differ by 2 percent. Figure 6 shows final horizontal phase space distributions. The most striking difference is the speed advance of UAL over CSRTrack by several orders of magnitude.

Table 2: UAL CSRtrack Comparison

Quantity	Unit	CSRtrack	UAL-NoVert	UAL-True
$\epsilon_{x,n}\|_{\rm in}$	mm.mrad	1.005	0.982	0.982
$\epsilon_{x,n}\|_{\rm out}$		74.10	72.6	57.2
$\epsilon_{y,n}\|_{\rm in}$	mm.mrad	1.0	1.04	1.04
$\epsilon_{y,n}\|_{\rm out}$		1.0	1.04	3.50
$\sigma_E\|_{\rm in}$	%	0.402	0.40	0.40
$\sigma_E\|_{\rm out}$		0.532	0.56	0.48
$\sigma_l\|_{\rm in}$	μm	200.2	199	199
$\sigma_l\|_{\rm out}$		190.3	191	184

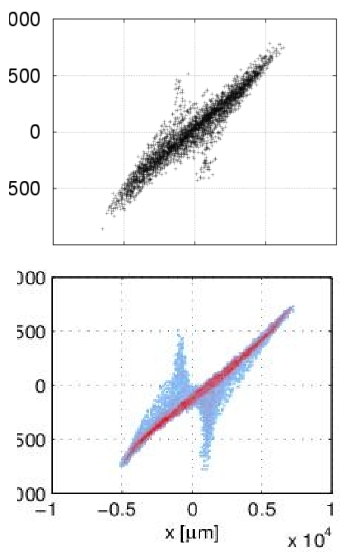

Figure 6: Output phase space distributions, UAL above, CSRtrack below, agree very well (except for a tiny relative horizontal displacement). Residual linear dispersion has been subtracted in these plots.

To investigate the effect of vertical forces, the UAL simulation was also run with all forces, including vertical, retained. According to this simulation the horizontal emittance increase, shown in Table 2, from 57.2 to 72.6 mm.mrad is an artefact of the neglect of vertical forces. Note the substantial increase in vertical emittance, from 1.04 to 3.50 mm.mrad, that accompanies the inclusion of vertical forces.

ACKNOWLEDGEMENTS

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